Toward high output-power nanogenerator

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In this paper, the factors that determine the power output of a piezoelectric nanowire (NW) nanogenerator (NG) have been analyzed. The output current is the sum of those contributed by all of the NWs while the output voltage is determined by the voltage generated by a single NW, the capacitance of the NW array and the system, and the contact resistance. By growing uniform ZnO NWs with diameters of ~100 nm and lengths of ~5 μm, the output current density and output voltage of the NG was improved to ~8.3 $\mu A/cm^2$ and 10 mV, respectively, which are 20–30 times higher than that we previously reported. A power generation density of ~83 nW/cm^2 is achieved by using a single layer NW NG. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2918840]

Energy harvesting from ambient environment has been an active research field.[1] Lately, it has drawn a lot of interest partly due to the invention of nanogenerator (NG) based on one-dimensional ZnO nanowires (NWs).[2] These devices with different configurations demonstrate the capability of harvesting energy from ambient vibrations in different media[3,4] under different frequencies.[4,5] In addition, several reports investigating the working mechanism of NG were published as well.[6,7] All of these work has established the basis for the self-powered nanosystem with applications ranging from biomedical to homeland security. A bottleneck technology in the application of NGs is the output power, especially the output voltage, which is dictated by individual NWs. In this letter, we report the fabrication and characterization of ZnO NW based NG that is able to generate a current of ~500 nA and voltage of ~10 mV with a surface area of 2×3 mm^2. The factors that govern the magnitude of the output voltage are analyzed. Based on the proposed model, future directions for improvements are presented. This is an important step toward high output-power NG.

The design and fabrication of NGs followed a similar method as previously reported[3,4] [Fig. 1(a)]. In short, well aligned ZnO NWs with an average length of ~5 μm were grown on GaN/AlN substrate through a vapor-solid process.[8] A thin layer of ZnO film was simultaneously grown on the bottom of the NWs, which served as a common electrode for the NG. A Pt coated, zigzag and trenched Si electrode was aligned on the top of the NWs. With the help of a flexible spacer, the spacing between the top electrode and bottom NWs was properly controlled to ensure enough spacing for the bending of the NWs. The fabrication was completed by packaging the device with water-proof polymer so that the testing could be carried out in aqueous environment. A well isolated water bath was employed to contain the packaged NG. A 41 kHz ultrasonic wave generator was used as the vibration source to excite the NG from the bottom of the water bath. The ultrasonic wave acts on the electrode and produces a vertical and/or lateral periodic relative displacement of the zigzag electrode with respect to the NWs, which results in bending and deflection of the NWs in any possible directions [Fig. 1(a)]. The built up strain in the NWs converts mechanical energy into electricity. Open circuit voltage and closed circuit current were measured according to the polarity shown in Fig. 1(a).

To ensure the quality of the NG, the NW arrays were carefully chosen so that the variance of the average length of the NW was minimal [Fig. 1(b)]. This is to maximize the number of NWs that would contribute to the power generation process while minimizing the parasitic capacitance that could bring down the voltage output. Our previous work[7] showed that a Schottky contact between the top electrode and bottom NW arrays is a must for the NG to be operational. Therefore, a current-voltage (*I-V*) measurement was performed to validate the contact to be Schottky before any further testing was carried out. The result is shown in Fig. 1(c).

The NG was then placed in the water bath to measure the closed circuit current and open circuit voltage. The ultrasonic wave generator was periodically turned on every other 15 s. Measurements were taken under both connection polarities to rule out any possible artifact caused by the measurement setup. Figure 2(a) shows the closed circuit current when the ultrasonic wave was turned on and off. The data clearly indicate that the current output was originated from the NG as a result of ultrasonic wave excitation, as the output coincided with the working cycle of the ultrasonic wave generator. Furthermore, the output signal switched in sign from positive to negative when the measurement polarity was switched from forward to reversed connection. Finally, there is no destabilization of the output amplitude over time in the graph. A similar pattern in the open circuit voltage output was also observed, as shown in Fig. 2(b). Both the current and the voltage outputs exhibit high levels for this type of NG, with a current of ~500 nA and voltage of ~10 mV. Considering the effective area of the NG (6 mm^2), it is equivalent to a current generation density of ~8.3 $\mu A/cm^2$, which is ~20 times higher than previously reported.[3] A power generation density of ~83 nW/cm^2 is reported, which shows a great potential to power nanosensors.[9]

The output current of the NG is the sum of those contributed by all of the active NWs, while the ultimate output voltage is determined by individual NW. Our previous cal-

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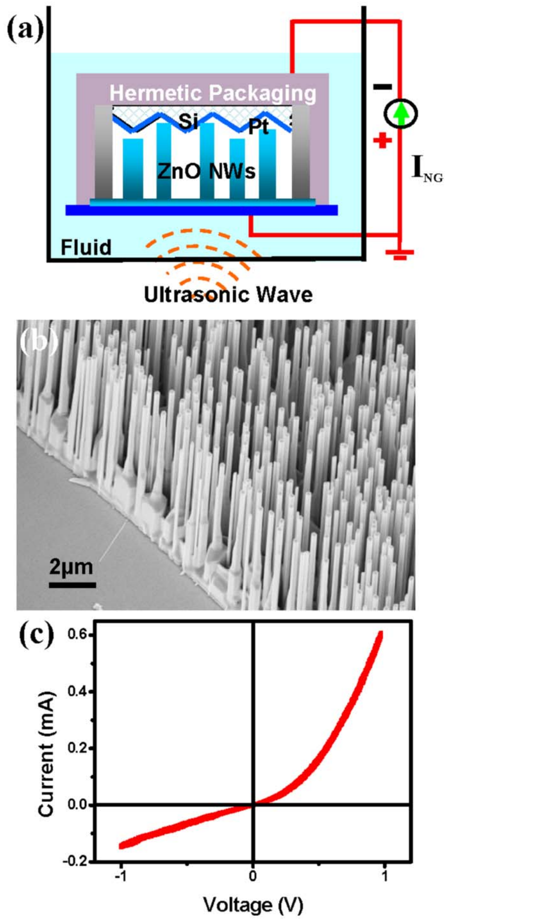

FIG. 1. (Color online) (a) Schematics of the measurement setup for characterizing an ultrasonic wave driven NG in aqueous condition. (b) Scanning electron microscope image of aligned ZnO NW arrays on GaN substrate. (c) *I-V* characteristics of the packaged NG to show a Schottky barrier at the interface between the zigzag electrode and the ZnO NWs.

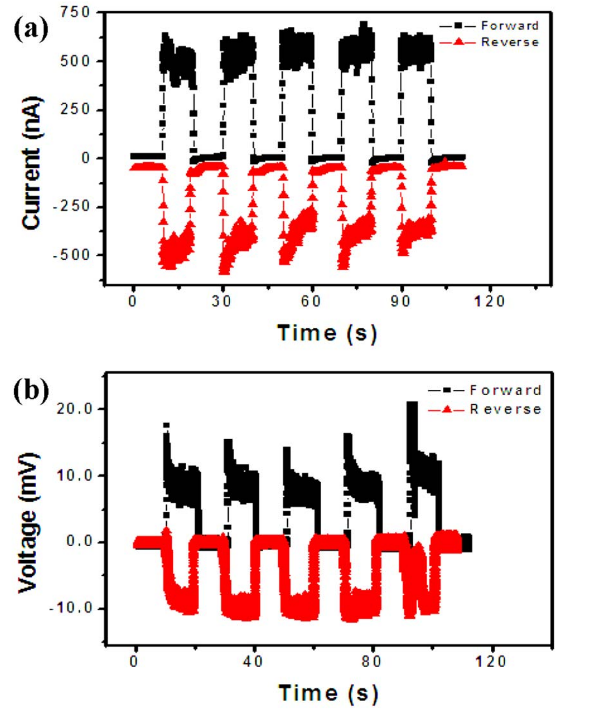

FIG. 2. (Color online) Performance of a packaged NG when periodically excited by ultrasonic wave. (a) Closed circuit current output and (b) open circuit voltage output measured at forward polarity (dark line) [see Fig. 1(a)], and reversed polarity (red line) connection with the measurement system.

culation shows that, based on an assumption that ZnO is nonconductive, the output voltage can be in the range of a fraction of a volt.[10] However, our experimental observation gives a much lower output in 1–20 mV. We now propose the following model to explain the received small output voltage.

Here, we consider a voltage generation model. Figure 3(a) represents the three possible situations for individual NWs during the voltage generation process. The first two stand for the NWs that are generating output current. They are illustrated by an equivalent circuit model shown at the left-hand side on Fig. 3(b). The circuit consists of a capacitor (c_0), which represents the capacitance between the NW and the electrode, two resistors (r_c and r_0), which represent the contact and NW inner resistances, respectively, a voltage source (v_0), which represents the voltage created in the NW by piezoelectric effect, and a diode, which represents the Schottky contact between the NW and the Pt coated electrode. The second possible situation is illustrated by NW III in Fig. 3(a), where the NW does not participate in the voltage generation process; instead, it is firmly in contact with the top electrode. This case is modeled by an equivalent circuit similar to that for NWs I and II, except with no voltage output. NW IV in Fig. 3(a) illustrates the third possible configuration between the NW and the top electrode, where the NW neither participates in the voltage generation process nor is in contact with the top electrode. Under such circumstance, a capacitor (c_0) is used to represent the capacitance between the NW and the top electrode. Figure 3(b) is the corresponding equivalent circuit of Fig. 3(a). In addition to the circuits that are corresponding to the NWs, a capacitor (c_s) that represents the effect from parallel plate electrodes and measurement environment is added at the right-hand side. To simplify the calculation, it is assumed that all of the variables that are represented by the same symbol have the same quantity. In reality, the resistance and capacitance for each NW can be different. Let q_0 denote the charge generated and effectively output from each NW during the bend-

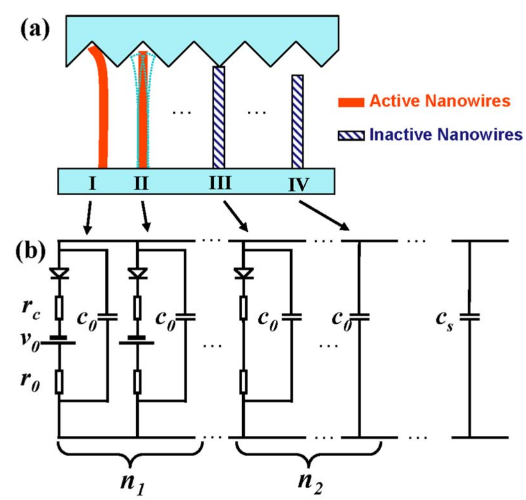

FIG. 3. (Color online) Equivalent circuit analysis of a NG. (a) Three different types of NWs are presented: NWs I and II are active NWs that output electricity; NW III is in contact with the top electrode but does not produce current; and NW IV is not in contact with the top electrode. (b) The corresponding circuit model, where c_s is added to represent the system capacitance.

ing process. To make the discussion simple, we consider a case that the system is approximately quasistatic at equilibrium, the voltage generated by a single NW may be written as

$$v_0 = \frac{q_0}{c_0}. \tag{1}$$

If a total of n NWs all simultaneously contribute to the energy generation process, and if the system capacitance c_s contributed by the electrodes is negligible, the measured voltage would be

$$v_0' = \frac{nq_0}{nc_0} = \frac{q_0}{c_0} = v_0. \tag{2}$$

Therefore, for any NG under such configuration, the maximum voltage output of the device is equal to the maximum voltage output of a single NW v_0.

For a nonideal case, such as in our experiment, let n_1 denote the number of active NWs that output electricity, and n_2 the number of inactive NWs that do not output electricity, as shown in Fig. 3(b), the system voltage output (v_s) is then

$$v_s = \frac{n_1 q_0}{(n_1 + n_2)c_0 + c_s}. \tag{3}$$

The total output current of the NG is

$$I_s \approx n_1 v_s/(r_0 + r_c). \tag{4}$$

For any given NG, n is the total number of NWs, $n=n_1+n_2$. Equation (3) gives a guideline for increasing the voltage output (v_s). The discussion given above serves as a qualitative guidance for understanding the signal output. In practice, the true output current/voltage has to consider the length of time during which the charges are released. Combining with the existing knowledge on the relationship between the morphology of ZnO NW arrays and the performance of NG, we summarize the key factors that are important to boost up the voltage output as follows:

(i) Increase the number of active NWs for participating electricity generation. This is crucial in determining the voltage output performance. There are two possible approaches to increase n_1. One is to utilize ZnO NW arrays with uniform size, especially uniform in length. The other approach is to pattern the NW arrays according to the dimension and shape of the top electrode. An increase in output voltage will be accompanied with a simultaneous increase in output current that is directly proportional to n_1.

(ii) Increase the charges generated by individual NW during the deflection process. This may be possible by increasing the magnitude of the external excitation, because the magnitude of the generated voltage is proportional to the deflection of the NW.[10]

(iii) Increase the total charge q_0 to be the output by a NW to the external load. This requires a great decrease in the contact resistance r_c between the metal electrode and the NW. We have designed an experiment to measure the contact resistance of a single ZnO wire with a metal tip [Fig. 4(a)]. By connecting a serial load R and applying a −2 V at the bottom of the wire, the voltage drop on the load R was measured [Fig. 4(b)].

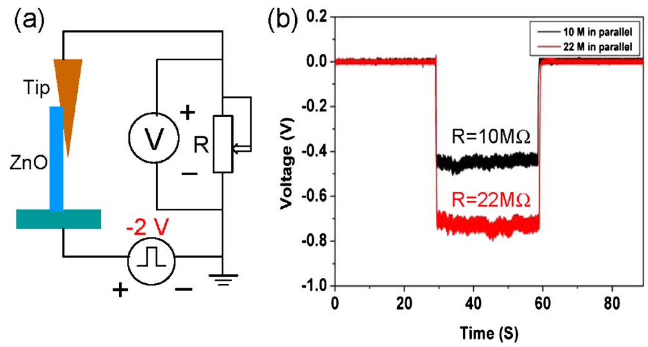

FIG. 4. (Color online) (a) Schematic setup to measure the contact resistance between a ZnO wire and a metal tip. The NW was in contact with the tip but without mechanical deformation. (b) Measured voltage drop on an external load with different resistance. The applied pulse voltage was −2 V.

From the data, the sum of the contact resistance and inner resistance of the wire $r_c + r_0$ was estimated to be ~35 MΩ. This large resistance dissipates a large voltage at the contact. It is thus essential to reduce the contact resistance to receive larger output voltage.

(iv) Optimize the electric conductivity of ZnO NW. Our previous work[7] has indicated the relationship between the carrier density and the performance of the NG. A too high conductivity destroys the Schottky contact at the interface, while a too low conductivity consumes too much voltage. It is expected that by tuning the carrier density to an optimal value, both the current and the voltage outputs can be significantly increased. However, the optimum value of the conductivity needs to be modeled with consideration the charge transport dynamics.

(v) Decrease the capacitance between individual NW and the top electrode, as well as the system capacitance. The size of the electrodes can make large contribution to the system capacitance. The other factor is the capacitance of the measurement circuit.

In summary, we have analyzed the factors that determine the output voltage and current of a NW NG. A voltage generation model is proposed to understand the received output voltage, based on which further improvements to increase the power output are discussed. This is an important step toward the design and fabrication of high output-power NG.

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[1]N. S. Shenck and J. A. Paradiso, IEEE MICRO **21**, 30 (2001).
[2]Z. L. Wang and J. H. Song, Science **312**, 242 (2006).
[3]X. D. Wang, J. Liu, J. H. Song, and Z. L. Wang, Nano Lett. **7**, 2475 (2007).
[4]X. D. Wang, J. H. Song, J. Liu, and Z. L. Wang, Science **316**, 102 (2007).
[5]Y. Qin, X. D. Wang, and Z. L. Wang, Nature (London) **451**, 809 (2008).
[6]J. H. Song, X. D. Wang, J. Liu, H. B. Liu, Y. L. Li, and Z. L. Wang, Nano Lett. **8**, 203 (2008).
[7]J. Liu, P. Fei, J. H. Song, X. D. Wang, C. S. Lao, R. Tummala, and Z. L. Wang, Nano Lett. **8**, 328 (2008).
[8]X. D. Wang, J. H. Song, P. Li, J. H. Ryou, R. D. Dupuis, C. J. Summers, and Z. L. Wang, J. Am. Chem. Soc. **127**, 7920 (2005).
[9]C. Yu, Q. Hao, S. Saha, L. Shi, X. Y. Kong, and Z. L. Wang, Appl. Phys. Lett. **86**, 063101 (2005).
[10]Y. Gao and Z. L. Wang, Nano Lett. **7**, 2499 (2007).